The H.E.S.S. Multi-Messenger Program: Searches For TeV Gamma-Ray Emission Associated With High-Energy Neutrinos

F. Schüssler*[1,a)], M. Backes[2], A. Balzer[3], F. Brun[4], M. Füssling[5], C. Hoischen[5], J-P. Lenain[6], M. Lorentz[1], I. Lypova[5], S. Ohm[5], D. Parsons[7] and A. Reimer[8] on behalf of the H.E.S.S. Collaboration

[1] *Irfu/CEA-Saclay, 91190 Gif-sur-Yvette Cedex, France*
[2] *University of Namibia, Windhoek, Namibia*
[3] *Universiteit van Amsterdam, 1012 WX Amsterdam, Netherlands*
[4] *Centre d'Etudes Nucléaires de Bordeaux-Gradignan, 33170 Gradignan, France*
[5] *Desy Zeuthen, Platanenallee 6, 15738 Zeuthen, Germany*
[6] *Sorbonne Universités, UPMC, Université Paris Diderot, Sorbonne Paris Cité, CNRS, LPNHE, 4 place Jussieu, F-75252, Paris Cedex 5, France*
[7] *Max Planck Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*
[8] *Universität Innsbruck, Innrain 52, 6020 Innsbruck, Austria*

[a)] Contact: contact.hess@hess-experiment.eu

Abstract. The observation of an astrophysical flux of high-energy neutrinos by the IceCube collaboration opened the path to multi-messenger studies searching for the origin of high-energy cosmic rays since the detected neutrinos possibly originate in hadronic interactions near cosmic-ray accelerators. Although the neutrino sky map shows no indication of localized sources so far, the angular resolution of individual track-like events is sufficiently small to search for associated gamma-ray emission with Imaging Atmospheric Cherenkov Telescopes like H.E.S.S.

Here we present the H.E.S.S. multi-messenger program to follow up on high-energy neutrino events. We show first results from searches for high-energy gamma-ray emission in spatial coincidence with neutrino events detected by the IceCube and ANTARES neutrino telescopes and discuss recent extensions towards a fully integrated real-time alert system between neutrino telescopes and the H.E.S.S. gamma-ray experiment.

INTRODUCTION

To locate the astrophysical sources and study the acceleration mechanisms able to produce high energy cosmic rays, fundamental particles with energies orders of magnitude above man-made accelerators, is one of the long standing quests in high-energy astrophysics. The main focus of the H.E.S.S. multi-messenger program is to exploit the intimate connection between high-energy neutrinos and γ-rays for these searches. Provided appropriate conditions of the environment of cosmic accelerators (e.g. magnetic fields, matter and field densities, etc.), high-energy (hadronic) particles are potentially undergoing interactions with matter and radiations fields within and/or surrounding the acceleration sites. The light mesons, predominantly pions, created in these interactions will decay by emitting both high-energy neutrino as well as γ-rays. For sources where the matter and radiation fields are not too dense to cause absorption of the emitted γ-rays, we can therefore hope to find spatial and temporal correlated emission of both messengers. Over the last years we started to exploit these potential correlations in searches for high energy γ-ray emission from regions surrounding the arrival direction of high energy neutrinos.

Two major instruments searching for astrophysical neutrinos are currently in operation: IceCube at the South Pole [3] and ANTARES [4] in the Mediterranean Sea. So far none of the neutrino telescopes has found any significant localized excess (e.g. [5]). Yet, a significant breakthrough has been made recently by the IceCube collaboration. In

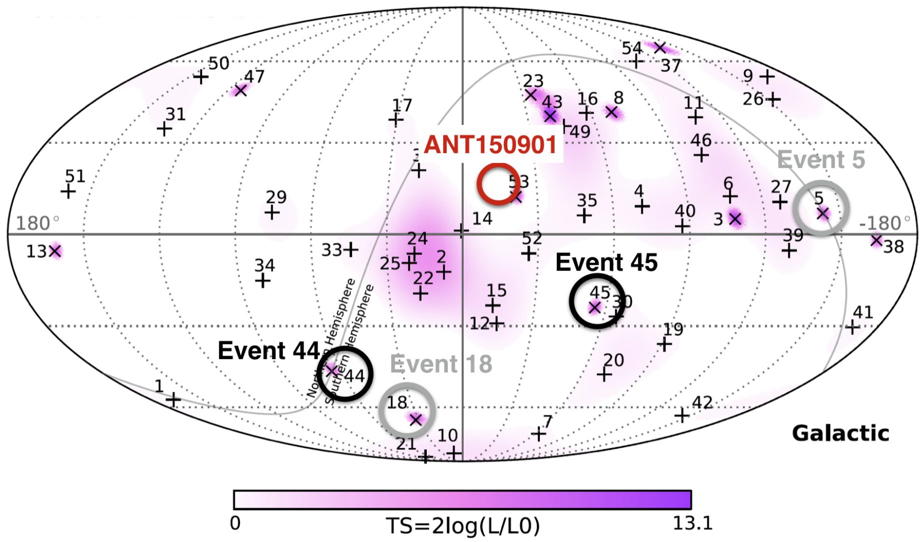

FIGURE 1. Arrival directions in Galactic coordinates of high-energy neutrino events detected by IceCube. Here we discuss the regions around the IceCube events IC-44 and IC-45 (highlighted by the black circles) and the ANTARES/Swift detection (red circle). H.E.S.S. observations around IC-5 and IC-18 (grey circles) have been reported previously [1]. Figure modified from [2].

four years of data, IceCube was able to single out 54 neutrinos with energies in the range of 60 TeV to 3 PeV that interacted within the instrumented volume (see Fig. 1). The atmospheric background contribution has been estimated as 12.6 ± 5.1 from cosmic ray muon events and $9^{+8}_{-2.2}$ atmospheric neutrinos events [2]. However, the origin of these neutrinos is unknown and no significant clustering or excess at small angular scales has been found so far.

SEARCHES FOR STEADY GAMMA-RAY EMISSION ASSOCIATED WITH HIGH-ENERGY NEUTRINOS

We here present searches for steady gamma-ray emitters in the vicinity of observed high-energy neutrino events, in particular the regions around the IceCube events IC-44 and IC-45 (highlighted by the black circles in Fig. 1). Two additional sky regions corresponding to IC-5 and IC-18 have been studied and presented previously [1].

H.E.S.S. analyses

Dedicated observations on the two IceCube events IC-44 and IC-45 were taken with the full array of H.E.S.S. Imaging Air Cherenkov telescopes during 2015.
IC-44 is a track-like event reconstructed to originate from RA=336.7 deg and Dec=0.04 deg with a median uncertainty of less than 1.2 deg. The energy deposited by the muon track within the IceCube detector, i.e. a lower bound on the energy of the incoming neutrino, has been estimated to $E_{\mathrm{dep}} = 84.6^{+7.4}_{-7.9}$ TeV. The region around the reconstructed neutrino direction has been observed with the H.E.S.S. IACTs for more than 7 h at an average zenith angle of 30°, resulting in an energy treshold of about 150 GeV. After correcting for acceptance effects the effective live time corresponds to 6.0 h. The recorded data were analyzed using the Model Analysis [6] with standard gamma-hadron separation and event selection cuts. The background could be determined from the dataset itself using the “ring background” method described in [7]. The map of Li & Ma significances [8] derived from the gamma-ray events exceeding the background expectation is shown in the left plot of Fig. 2. The emission from the region is fully compatible with the background expectation and we conclude that no gamma-ray flux has been detected.

IC-45 is another track-like event recorded by IceCube. Its incoming direction has been reconstructed to Ra=218.85 deg and Dec=−86.25 deg with a median uncertainty of less than 1.2 deg. $E_{\mathrm{dep}} = 429.9^{+57.4}_{-49.1}$ TeV have been deposited in the IceCube detector. It should be noted that the event has the particularity of being almost vertically

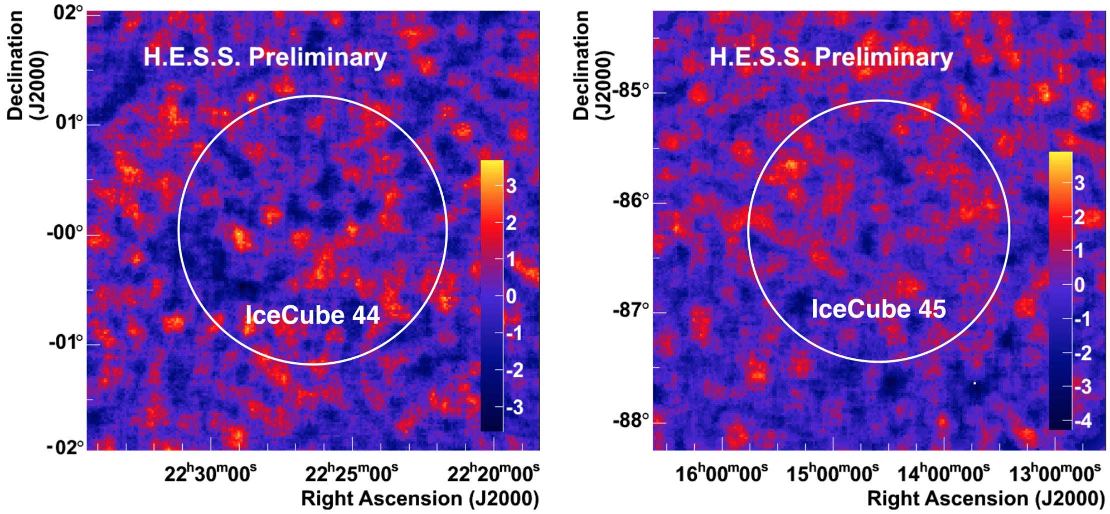

FIGURE 2. Significance maps derived from H.E.S.S. observations of the regions around the arrival directions of IceCube events 44 (left) and 45 (right). The circles denotes the individual median angular uncertainty on the neutrino directions provided by IceCube [2].

downgoing at the site of the IceCube detector, but no coincident signal has been observed in the IceTop air shower array covering the in-ice neutrino telescope. This hints to the absence of an extensive air shower accompanying the high-energy neutrino and further increases the probability of the event being of astrophysical origin. The region around the neutrino event IC-45 has been observed for almost 4.5 h (effective live time after acceptance correction of 3.0 h) with the H.E.S.S. Cherenkov telescopes at zenith angles around 63°. These relatively high zenith angles lead to an energy threshold of about $E_{\rm thr} \approx 1.5\,\mathrm{TeV}$. The data were again analyzed using the Model Analysis [6] with standard gamma-hadron separation and event selection cuts and the "ring background" method. No significantly enhanced gamma-ray emission has been detected and the resulting map (cf. Fig. 2, right) is fully compatible with the background expectation.

Fermi-LAT analyses

To extend the energy range covered by the analysis of the region of interests (ROIs), we analyzed data from Fermi-LAT gamma-ray detector. We used all data in the energy range $100\,\mathrm{MeV} - 300\,\mathrm{GeV}$, recorded between the mission start (2008-08-04) and 2016-05-01. The latest release of the Fermi-LAT data, PASS 8, has been analyzed using the P8R2_SOURCE_V6 instrument response function and applying the default event selection criteria proposed by the Fermi collaboration.The count maps of the selected gamma-ray events from a $10^\circ \times 10^\circ$ region centered at the two neutrino events is shown in the left column of Fig. 3. The gamma-ray emission observed in the Fermi-LAT data has been modeled using the information given in the 3FGL catalogue [9], fixing the parameters for known sources further away than 3 deg from the center of the ROI to the 3FGL values. An additional point-like source with a power-law energy spectrum has been added to the description before fitting the model parameters to the count map of the selected events. The fit did not yield significant emission from the additional putative source in either of the studied fields (cf. Fig. 3).

We note that the uncertainty region of IceCube-44 comprises a 3FGL source (3FGL J2227.8+0040) which might be associated with BL Lac like object PMN J2227+0037 with unknown redshift. It should be noted that the chance probability of finding a known γ-ray emitting AGN within the error-box of a track-like high-energy neutrino detected by IceCube is significant (e.g. [10]).

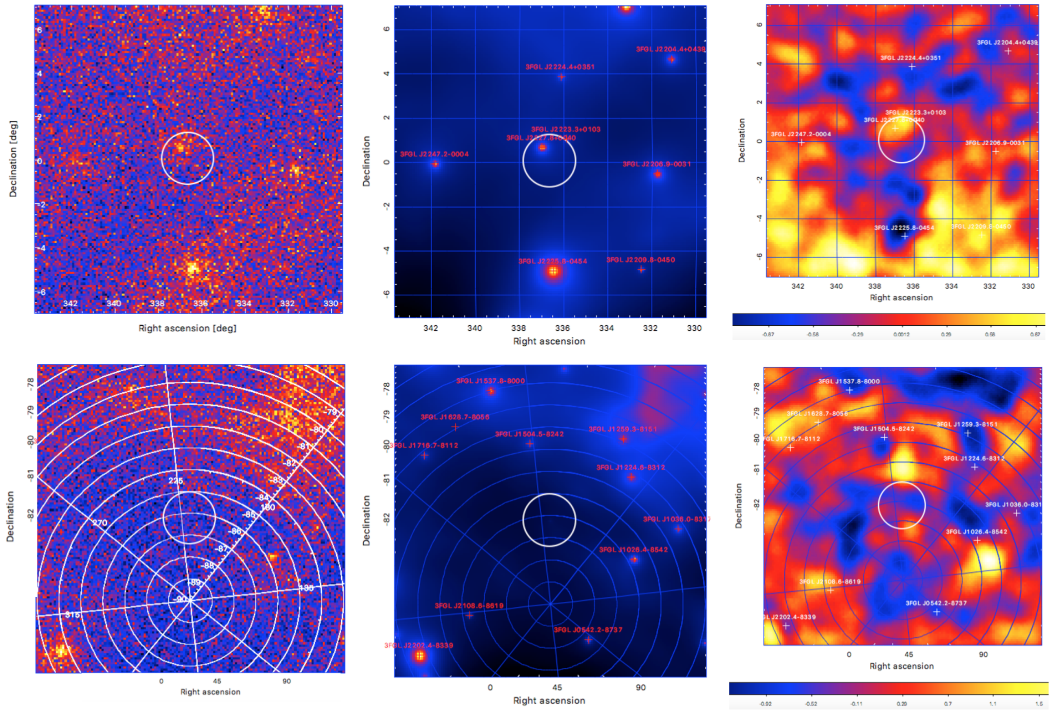

FIGURE 3. Region around the studied IceCube events as seen by the Fermi-LAT gamma-ray observatory. The top row shows IC-44, whereas the bottom row corresponds to IC-45. Left plots: Count maps of γ-rays detected by Fermi-LAT in equatorial coordinates. Center plots: Maps showing the model of γ-ray sources fitted to the Fermi-LAT data. Right plots: Normalized residual maps. The circles denotes the individual median angular uncertainty on the neutrino directions provided by IceCube [2].

Upper limits on the γ-ray flux

Given the absence of a significant high energy γ-ray signal in the observed regions, upper limits on the VHE and HE γ-ray flux have been derived. Flux limits have been calculated for a point-like source in the center of the ROI and for a generic E^{-2} energy spectrum. We refrain from scanning the uncertainty region as, thanks to the large field of view of both H.E.S.S. and Fermi-LAT and good observational coverage of the ROIs, the sensitivities are roughly flat throughout the neutrino uncertainty regions. The derived upper limits can therefore be considered representative for the whole area. Following the method introduced by Feldman & Cousins [11], the obtained 99 % confidence level limits from the H.E.S.S. observations are shown as black triangles in Fig. 4. The limits derived from Fermi-LAT data are shown as a black lines with arrows.

The expectation from the neutrino observations is illustrated in the figure via the red lines. IceCube measured a diffuse, all-sky neutrino flux to: $E^2 \times \Phi(E) = 2.2 \pm 0.7 \times 10^{-8} (E/100\,\mathrm{TeV})^{-0.58}\,\mathrm{GeV\,cm^2\,s^1\,sr^1}$. This flux is illustrated by the solid red lines in Fig. 4, which were derived by distributing the all-sky flux over 1000 putative sources, a number currently not excluded by the searches for point-like neutrino sources. The derived flux can therefore be considered as an upper-bound on the expected neutrino flux per contributing source. The conversion into a γ-ray flux (dashed red lines in Fig. 4) uses a parametrization derived from Monte Carlo simulations of the hadronic interactions connecting neutrino and γ-ray fluxes via the decay of charge and neutral pions created in pp interactions within or close to a generic hadronic accelerator. This conversion relies on several assumptions on the source environment like sufficiently low radiation and matter densities to prevent γ-ray absorption, pion-matter and $p\gamma$ interactions. Details of these assumptions are given in [12].

Unlike neutrinos, high energy γ-ray photons are absorbed by pair production on the extra-galactic background light (EBL). This process can be described by $\Phi_{\mathrm{obs}} = \Phi_{\mathrm{source}} \times e^{-\tau}$, where the optical depth τ is a function of the energy E_γ and the redshift of the source z_s. For sufficiently distant sources, i.e. sufficiently large optical depths, the gamma-ray flux will get absorbed and could therefore become compatible with the upper limits derived from the γ-ray measurements. We illustrate this effect using the EBL model from [13] and assuming several source distances (dotted red lines).

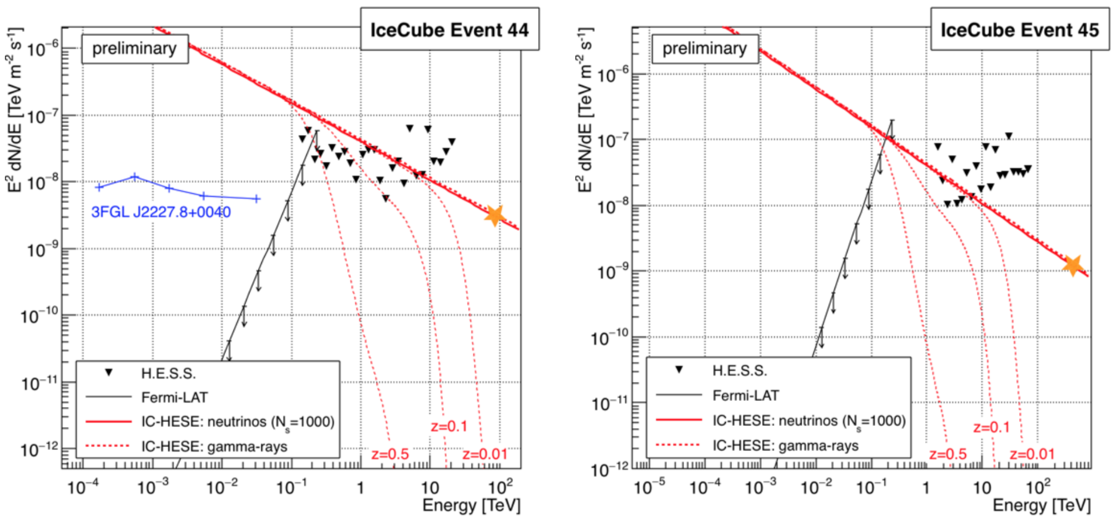

FIGURE 4. VHE gamma-ray flux limits Φ_{UL} at 99 % CL derived from the H.E.S.S. (black triangles) and Fermi-LAT (black arrows) observations assuming a point-like source with an E^{-2} energy spectrum. The estimate of the γ-ray flux (solid, red line) has been derived from the IceCube measurement of a diffuse neutrino flux (dashed red line). The energy deposited by the neutrinos events is shown as yellow stars.

TOWARDS REAL-TIME MULTI-MESSENGER ASTRONOMY AT TEV ENERGIES

After the follow-up of the archival IceCube events presented above and previously in [1], the H.E.S.S. multi-messenger program is now transiting towards a new phase during which we are trying to open a new window to the high-energy universe: real-time multi-messenger astronomy at TeV energies. The technical basis for this endeavor is a novel alert system that has been implemented recently [14]. This system is based on the VoEvent format and is fully integrated into the DAQ and the control system of the H.E.S.S. experiment, thus allowing for rapid, automatic reactions to incoming ToO requests and alerts. Since early 2016 we are using this system to receive real-time alerts from both the IceCube and ANTARES neutrino telescopes.

H.E.S.S. follow-up of ANTARES/Swift ATEL#7987

A first H.E.S.S. search for transient sources using a multi-messenger approach was performed in September 2015 with the follow-up of the ANTARES neutrino alert ANT150901A. After the detection of a high-energy neutrino by the online reconstruction of the ANTARES neutrino telescope on September 1st, 2015, at 07:38:25 UT, an alert has been issued to a variety of optical telescopes and the Swift X-ray satellite [16]. 10 hours later Swift observed the region around the neutrino direction (RA=246.43 deg, Dec=−27.39 deg with an of uncertainty radius of 18 arcmin) and discovered an unkown, relatively bright ($\Phi = 5 \times 10^{-13} - 1.4 \times 10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ at $0.3 - 10\,\mathrm{keV}$) and variable X-ray source. These observations where reported in ATEL#7987 [15] on 3 Sep 2015 at 12:18 UT.

We immediately scheduled H.E.S.S. follow-up observations which started September 1st, 2015, at 18:58 UT as soon as good observation conditions were reached. The significance map derived from 1.5 h of observations is shown in Fig. 5. The uncertainty on the direction of the high-energy neutrino is shown as white circle and the location of the Swift source is indicated by the white marker. Consequently an upper limit on the gamma-ray flux has been derived as $\Phi(E > 320\,\mathrm{GeV}) < 2.4 \times 10^{-7}\,\mathrm{m^{-2}\,s^{-1}}$ ()99 % C.L.). It should be noted that the extensive multi-wavelength follow-up of ATEL#7987 lead to the conclusion that the Swift X-ray source is due to a young star (USNO-B1.0 0626-0501169) and thus unrelated to the neutrino, which may be of atmospheric origin.

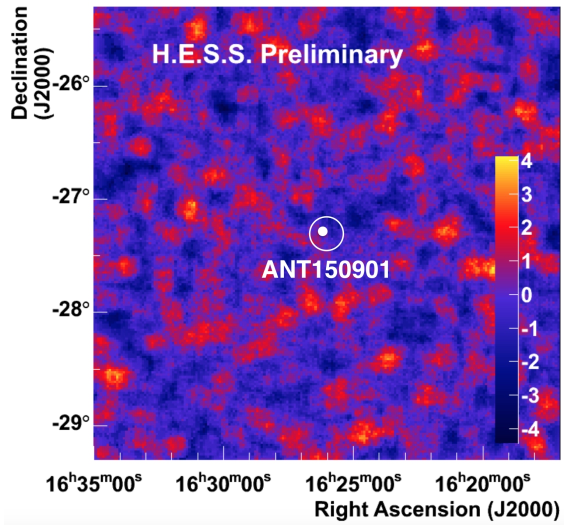

FIGURE 5. Significance map derived from H.E.S.S. observations of the region around the region of the ANTARES high-energy neutrino alert ANT150901A published in ATEL#7987 [15]. The uncertainty of the neutrino direction (0.3 deg) is shown as white circle and the location of the Swift source is indicated by the white marker.

ACKNOWLEDGMENTS

The support of the Namibian authorities and of the University of Namibia in facilitating the construction and operation of H.E.S.S. is gratefully acknowledged, as is the support by the German Ministry for Education and Research (BMBF), the Max Planck Society, the German Research Foundation (DFG), the French Ministry for Research, the CNRS-IN2P3 and the Astroparticle Interdisciplinary Programme of the CNRS, the U.K. Science and Technology Facilities Council (STFC), the IPNP of the Charles University, the Czech Science Foundation, the Polish Ministry of Science and Higher Education, the South African Department of Science and Technology and National Research Foundation, the University of Namibia, the Innsbruck University, the Austrian Science Fund (FWF), and the Austrian Federal Ministry for Science, Research and Economy, and by the University of Adelaide and the Australian Research Council. We appreciate the excellent work of the technical support staff in Berlin, Durham, Hamburg, Heidelberg, Palaiseau, Paris, Saclay, and in Namibia in the construction and operation of the equipment. This work benefited from services provided by the H.E.S.S. Virtual Organisation, supported by the national resource providers of the EGI Federation.

We acknowledge valuable discussions facilitating the preparation of the observations discussed here with colleagues from the IceCube Collaboration: E. Bernardini, J. Dumm, W. Giang, A. Stasik, T. Kintscher and C. Kopper as well as M. Ageron, D. Dornic and A. Mathieu from the ANTARES Collaboration.

F. Schüssler gratefully acknowledges financial support by the Programme National Hautes Energies (PNHE).

REFERENCES

[1] F. Schüssler et al. (H.E.S.S. Collaboration), 34th International Cosmic Ray Conference (2015).
[2] C. Kopper et al. (IceCube Collaboration), 34th International Cosmic Ray Conference, PoS p. 1081 (2015).
[3] R. Abbasi et al. (IceCube Collaboration), NIM A **601**, p. 294 (2009).
[4] M. Ageron et al. (ANTARES Collaboration), NIM A **656**, p. 11 (2011).
[5] M. G. Aartsen et al. (IceCube collaboration), ApJ **796**, p. 109 (2014).
[6] M. de Naurois and L. Rolland, APP **32**, 231–252 (2009).
[7] D. Berge, S. Funk, J. Hinton et al., A&A **466**, p. 1219 (2007).
[8] T.-P. Li and Y.-Q. Ma, ApJ **272**, 317–324 (1983).
[9] F. Acero et al. (Fermi-LAT Collaboration), APJ Supplement Series **218**, p. 23 (2015).
[10] A. M. Brown, Jenni Adams, and Paula M. Chadwick, **451**, 323–331 (2015).
[11] G.J. Feldman and R.D. Cousins, Phys. Rev. D **57**, 3873–3889 (1998).
[12] A. Kappes, J. Hinton, C. Stegmann and F. Aharonian, Astrophys. J. **656**, 870–878 (2007).
[13] A. Franceschini, G. Rodighiero and M. Vaccari, **487**, p. 837 (2008).
[14] C. Hoischen et al. (H.E.S.S. Collaboration), Baikal Three Messenger Conference (2016).
[15] D. Dornic et al. (ANTARES/TAToO Collaboration), The Astronomer's Telegram #7987 (2015).
[16] M. Ageron et al. (ANTARES/TAToO Collaboration), APP **35**, 530–536 (2012).
[17] M. de Naurois and M. Holler, 34th International Cosmic Ray Conference (2015).